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Microclimatic and Rooting Characteristics of Narrow-Row versus Conventional-Row Corn

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ABSTRACT

Narrow-row corn (*Zea mays* L.) has been advocated in recent years for bolstering production, but previous studies have failed to elucidate the complexity of factors that promote the production of corn sown in narrow rows. This study was undertaken to identify those agronomic and microclimatic factors that influence grain yield of corn grown in narrow and wide conventional rows. A split plot experimental design was established near Morris, MN, in 1998 and 1999 with row spacing (0.38, 0.57, and 0.76 m) as the main treatment and corn hybrid (Pioneer 3893 and DeKalb 417) as the secondary treatment. Root length density, crop water use, interception of photosynthetically active radiation (PAR), soil temperature, and soil evaporation were measured in each row-spacing treatment during the growing season. Grain yield and water use of narrow-row corn equaled, or even exceeded, that of wide, conventional-row corn. Narrow-row corn had a more uniform root distribution and intercepted 5 to 15% more PAR on clear days, the latter of which likely aided in suppressing soil temperatures and evaporation during vegetative growth compared with corn grown in conventional rows. The results of this study suggest that any yield advantage to growing corn in narrow rows may result from establishing a more uniform root and leaf distribution that aids in exploiting soil water and light resources and reducing soil temperatures and evaporation compared with corn grown in wide conventional rows.

Seed row spacing is an agronomic management strategy used by producers to optimize the husbandry of the soil and plant ecosystem from sowing to harvest with the goal of bolstering the production of crops. Although the optimum row spacing varies among plant genus, yields will generally be maximized by sowing in rows that result in an equidistant spacing among plants. Indeed, equidistant spacing among plants optimizes the utilization of nutrients, water, and solar radiation (Shubeck and Young, 1970; Bullock et al., 1988).

Narrow-row corn (*Zea mays* L.) has been advocated in recent years as a technique to enhance grain yield (Orchard, 1998). Porter et al. (1997), for example, reported a 7% increase in grain yield in Minnesota while Nielsen (1988) found about a 3% higher grain yield in Indiana for corn grown in narrow rows (spacing less than 0.76 m) versus conventional rows (spacing of 0.76 m). More recently, Widdicombe and Thelen (2002) found that corn grown in narrow rows (spacing of 0.38 and 0.56 m) produced as much as 4% more grain compared with corn grown in conventional rows (spacing of 0.76 m) in Michigan. These differences in yield associated with row spacing appear to be accentuated for corn grown at more northerly locations within the U.S. Corn Belt. Paszkiewicz (1997), for example, found that corn grown in narrow rows to the north of Interstate 90 (44° N latitude) resulted in an 8% higher grain yield while that grown in narrow rows to the south of Interstate 90 resulted in a 4% higher grain yield compared with corn grown in wide conventional rows. Not all studies, however, have reported a positive response in yield to growing corn in narrower rows (Ottman and Welch, 1989; Westgate et al., 1997). In fact, Pedersen and Lauer (2003) found an 11% lower yield for corn grown in 0.19-m rows versus 0.38- and 0.76-m rows in Wisconsin while Farnham (2001) found a 2% lower yield for corn grown in 0.38-m rows versus 0.76-m rows in Iowa.

Hybrid and plant population may influence the yield response of corn to row spacing (Tollenaar, 1989). Farnham (2001) observed a significant hybrid × row spacing interaction among six hybrids grown in narrow and wide conventional rows in Iowa. Nielsen (1988) and Widdicombe and Thelen (2002), however, found that higher yields were attained for corn grown in narrow rows versus wide conventional rows irrespective of hybrids and plant populations tested in Indiana and Michigan.

Crop row spacing influences canopy architecture, which is a distinguishing characteristic that affects the utilization of light, water, and nutrients. Earlier canopy closure of corn grown in narrower rows has been found to enhance light interception (Ottman and Welch, 1989; Andrade et al., 2002) as well as suppress weed growth (Forcella et al., 1992). Westgate et al. (1997), however, reported that light interception was not affected by corn row spacing; they found no yield advantage to growing corn in narrow (spacing of 0.38 m) rows versus conventional (spacing of 0.76 m) rows over two growing seasons in Minnesota. Crop row spacing can also influence soil water utilization. Yao and Shaw (1964), for example, reported corn grown in 0.53-m rows used less water and used water more efficiently than that grown in 0.81- or 1.07-m rows. Karlen and Camp (1985) hypothesized that corn spaced more uniformly would reduce intrarow competition for water and thereby bolster yield.

Narrow-row corn has been advocated for enhancing grain production in corn due to less weed competition and better resource (soil water, solar radiation, and nutrients) utilization. Previous studies, however, have failed to adequately characterize the complexity of factors that bolster production of narrow-row corn. Therefore, the purpose of this study was to characterize root growth,

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Abbreviations: LAI, leaf area index; PAR, photosynthetically active radiation.

water use, and microclimatic factors (e.g., soil temperature and evaporation) that may bolster grain production of corn grown in narrow rows versus wide conventional rows.

MATERIALS AND METHODS

This study was conducted at a field site located near Morris, MN (45°35′ N, 95°55′ W). Experimental treatments were established in 1998 and 1999 on a Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) with ≤0.5% slope. Wheat (*Triticum aestivum* L.) was grown at the field site the year preceding the establishment of treatments in 1998 while corn was grown at the site the year preceding the 1999 growing season. The field site was cultivated with a chisel plow in autumn and with a disk to incorporate fertilizer at a rate of 170 kg N ha^{-1}, 40 kg P ha^{-1}, and 40 kg K ha^{-1} in the spring before establishing the experimental treatments.

Agronomic Protocol

The experimental design was split plot with four replications. Row spacing was the main treatment and included corn sown in 0.38-, 0.57-, and 0.76-m rows. Corn hybrid was the secondary treatment and included Pioneer 3893 and DeKalb 417. Pioneer 3893 has a relative maturity of 90 d, is medium in stature, exhibits excellent early-season growth, tolerates drought, and has an upright, narrow-leaf structure. DeKalb 417 has a relative maturity of 91 d, is medium to tall in stature, exhibits excellent early-season growth, tolerates drought, and has a horizontal, wide-leaf structure. Individual plots were 9 by 15 m.

Corn was sown with a commercial corn planter at 150 000 seeds ha^{-1} in north–south rows on 4 May 1998 and 19 May 1999. Weeds were controlled by hand or with an herbicide during the growing season. Plant stands were thinned by hand to 75 000 plants ha^{-1} shortly after emergence. Final plant population was determined at harvest on 17 Sept. 1998 and 27 Sept. 1999. Harvest consisted of removing ears from stalks by hand and then clipping the stalks at the soil surface from an area of 3.0, 4.6, and 6.1 m^2 (equivalent to four adjacent crop rows, each 2 m long) within the 0.38-, 0.57-, and 0.76-m row-spacing treatments, respectively. The ear and stalk samples were dried at 60°C until constant weight, after which the ears were shelled to determine grain yield; residue biomass consisted of all remaining plant parts (stalks, leaves, husks, and cobs).

Root length density of Pioneer 3893 was measured on 20 July 1998 and 27 July 1999. These dates correspond to the silk or R1 developmental stage, which generally coincides with maximum root length density in corn (Durieux et al., 1994). Soil core samples (76-mm diam.) were extracted by machine to a depth of 1.5 m within and between rows at two locations in each plot. At each location, one core sample was taken midway between two adjacent corn rows, and two samples were taken between two adjacent plants within a crop row. The intrarow core samples were taken next to the stalk and midway between plants. Samples were sectioned to ascertain root length density at depth increments of 0.1 m for the 0- to 0.5-m depth and at depth increments of 0.2 m for the 0.5- to 1.5-m depth. The sectioned intrarow samples were consolidated into a single sample for each depth interval at each location. Root length density was determined by the line intersect method (Bohn, 1979). This method required soaking the soil samples in softened water and extracting the root material by sieving (nominal sieve openings of 1.0 and 0.5 mm). Root and other organic material retained by the sieves were placed in a glass dish filled with water. A grid was placed beneath the dish, and root length was then determined by counting the number of roots that intersected each grid line.

Microclimate

Instrumentation to measure crop water use, light interception, soil temperature, and soil evaporation was installed in each plot of Pioneer 3893 at the time of seedling emergence. Soil water content was assessed weekly in each plot by neutron attenuation and at the beginning and end of the season by gravimetric sampling. Soil water content was measured at 0.3-m depth increments to a depth of 2.1 m in the seed row and to a depth of 0.6 m between seed rows. Soil matric potential was measured using tensiometers placed at a depth of 1.75 and 2.0 m in one replication of each row-spacing treatment. These measurements, made weekly, aided in determining the direction and magnitude of water flow below the root zone.

Crop water use was calculated as the difference between precipitation plus soil water extraction and runoff. Water flow below the root zone was also considered in determining crop water use; downward flow signified drainage while upward flow contributed to evapotranspiration. Runoff was assumed negligible due to few intense rainfall events (two events in 1998 and 1999 that exceeded 40 mm d^{-1}), no visual rills or washing of debris at the soil surface immediately following these rainfall events (except on 14 July 1998 when washing of debris was apparent at the soil surface on all plots following a 49-mm precipitation event), and nearly level topography. Precipitation, soil water content, and water flow below the root zone were measured from emergence to harvest. Precipitation was measured daily at a nearby microclimate station (100 m from the experimental plots). Water flow below the root zone (WFBR) was determined according to:

$$\mathrm{WFBR} = -k(\Delta h/\Delta z) \quad [1]$$

where k is the hydraulic conductivity (cm s^{-1}) and Δh is the difference in hydraulic potential (cm) over the depth interval Δz (cm). Drainage occurred when water flow below the root zone was negative. Hydraulic conductivity was assumed to vary with soil water matric potential according to Campbell (1985):

$$k = k_s(\psi_e/\psi)^{(2+3/b)} \quad [2]$$

where k_s is the saturated hydraulic conductivity (cm s^{-1}), ψ_e is the air entry matric potential (cm), ψ is the matric potential (cm), and b is the slope of the natural log of the water retention curve. Sharratt and Gesch (2004) previously measured k_s, ψ_e, and b at the field site, but these parameters were measured at a depth of 1.0 to 1.25 m. Values of k_s, ψ_e, and b required for calculating water flow in this study (at a depth of 1.75 to 2.0 m) may differ from those previously measured due to changes in soil texture and bulk density (Campbell, 1985) with depth. Bulk density, but not texture, appears to increase with depth (from about 1.6 Mg m^{-3} at 1 m to 1.7 Mg m^{-3} at 2 m) based on pedon descriptions for Barnes loam near Morris, MN (USDA Natural Resources Conservation Service, 2004). Equations presented by Campbell (1985) suggest that the greater apparent bulk density at 2 m will reduce k_s and ψ_e by respectively 55 and 45% of the measured values at a depth of 1 m but will have little effect on b. These revised estimates of k_s and ψ_e were used to calculate hydraulic conductivity.

Light interception was determined from incident PAR measured at the soil surface (I_s) and above the crop canopy (I_o). Intercepted PAR, calculated as $I_o - I_s$, neglected PAR reflected from the canopy and soil surface (about 40 μmol m^{-2} s^{-1}). The fraction of I_o intercepted was calculated as $(I_o - I_s)/I_o$. Photosynthetically active radiation was simultaneously measured at the soil surface using a linear quantum sensor (LI-191SA, LI-COR, Inc., Lincoln, NE) and above the crop canopy using a quantum sensor (LI-190SB, LI-COR, Inc., Lincoln, NE). The linear quantum sensor was placed diagonally across one 0.56-m interrow, one 0.76-m interrow, or two adjacent 0.38-m interrows. Both ends of the sensor were positioned in the center of the crop row. Measurements were made at three locations in each plot within 1 h of solar noon on clear days: 27 May, 16 June, 24 June, 26 June, 1 July, 8 July, and 13 July 1998; 4 June, 14 June, 17 June, 24 June, 2 July, and 6 July 1999. Sensors were intercalibrated by measuring I_o with both sensors after completing a series of measurements from a single replication. Measurements were initiated after seedling emergence and terminated near tasseling in 1998 and at about the V13 stage of development in 1999. Light interception was expressed as a function of thermal time from emergence where thermal time was computed using a minimum temperature threshold of 10°C and a maximum temperature threshold of 30°C (Swan et al., 1987).

Soil temperatures were measured at a depth of 10, 50, and 100 mm both within and between crop rows at three locations in each plot. Temperatures were measured using thermocouples; thermocouples at each depth were wired in parallel to obtain an average interrow and intrarow temperature. Thermocouples were monitored using a data logger, which sampled every 60 s and recorded hourly.

Soil evaporation was measured using microlysimeters similar to the design of Boast and Robertson (1982) with some modification. The microlysimeter consisted of two plastic pipes, one slightly larger (inside diameter, 92 mm; outside diameter, 101 mm) than the other (inside diameter, 81 mm; outside diameter, 89 mm) such that the smaller pipe fit inside the larger pipe. The larger pipe was 0.15 m long and reamed at one end to accommodate insertion of a 5-mm-thick 96-mm-diam. aluminum plate. The aluminum plate prevented moisture exchange but facilitated heat exchange between the soil inside and outside the microlysimeter. The larger pipe was semipermanently installed in the soil profile such that the aluminum cap made good contact with the subsoil and the top of the pipe was level with the soil surface. The smaller pipe was 0.15 m long and tapered at one end to facilitate insertion into the soil until the soil surface was level with the top of the pipe. The pipe was then excavated to extract an intact soil column. The bottom of the soil column was trimmed level with the end of the pipe. The outside of the pipe was cleaned, weighed, and then placed inside the larger-diameter pipe. The top of the smaller pipe protruded 5 mm above the soil surface, and the gap between the top of the smaller- and larger-diameter pipes was sealed with a rubber ring. The smaller-diameter pipe was reweighed every 24 h during an evaporation event (period of time with no precipitation). Soil inside the smaller-diameter pipe was discarded after 48 h or a rainfall event. Soil evaporation was measured midway between crop rows at three locations in each plot beginning 3 June, 22 June, 30 June, 8 July, and 13 July 1998 and 26 May, 14 June, 16 June, 21 June, 1 July, 6 July, 12 July, and 14 July 1999.

Homogeneity of sample variance was tested before analyzing agronomic data using a split-plot design and microclimatic data using a randomized block experimental design in analysis of variance. Least significant difference (LSD) was used to separate treatment effects when significant F values ($P \leq 0.10$) were determined in the analysis of variance.

RESULTS AND DISCUSSION

Past observations suggest that corn uses water more efficiently when grown in narrower rows (Yao and Shaw, 1964); thus corn production in water-limiting environments may be favored by narrow-row corn. The climatic conditions of this study, however, proved to be wetter than is typical for west-central Minnesota in the northern U.S. Corn Belt. For example, precipitation during both growing seasons (May through September) at Morris, MN, was above the 30-yr normal (410 mm) and totaled 430 mm in 1998 and 490 mm in 1999. Seasonal air temperatures were also above normal (18.0°C) and averaged 19.6°C in 1998 and 18.5°C in 1999.

Agronomic Characteristics

Final plant population and ears per plant did not vary across row-spacing treatments in this study. Plant populations averaged 76 300 and 75 400 plants ha^{-1} in 1998 and 1999, respectively, and ears per plant averaged 1.0 both years. Corn grain yield did not reflect differences in precipitation across years but varied from 10 610 kg ha^{-1} in 1998 to 9945 kg ha^{-1} in 1999. Corn row spacing did not influence grain yield in 1998 (Table 1) but did affect yield in 1999 as corn grown in 0.38-m rows produced 10% more grain than corn grown in 0.76-m rows. This higher percentage in grain yield associated with narrower rows appears to be consistent with observations made by Paszkiewicz (1997), who found that corn grown in narrower rows resulted in an 8% higher grain yield at locations north of Interstate 90 in the USA. Although corn grown in narrower rows produced more grain in 1999, corn row spacing did not influence grain yield of Pioneer 3893 (probability of type I error or P = 0.38) or DeKalb 417 (P = 0.22) when averaged over both years of this study.

Corn row spacing also influenced residue biomass

Table 1. Agronomic and water use characteristics of corn grown in 0.38-, 0.57-, and 0.76-m rows near Morris, MN.

Year	Row spacing	Grain yield D†	Grain yield P	Harvest index D	Harvest index P	Water use	Water use efficiency
	m	kg ha^{-1}	kg ha^{-1}			mm	kg ha^{-1} mm^{-1}
1998	0.38	10 630	10 789	0.53	0.55	542	19.9
	0.57	10 729	10 855	0.54	0.54	543	20.0
	0.76	10 025	10 636	0.54	0.56	529	20.1
	LSD‡	ns		ns		ns	ns
1999	0.38	10 626	10 418	0.54	0.57	494	21.1
	0.57	9 846	9 803	0.55	0.54	467	21.0
	0.76	9 603	9 382	0.53	0.55	462	20.3
	LSD	432		ns		20	ns

† D is DeKalb 417 and P is Pioneer 3893.

‡ LSD is least significant difference at $P \leq 0.1$ for comparing row spacing within a hybrid.

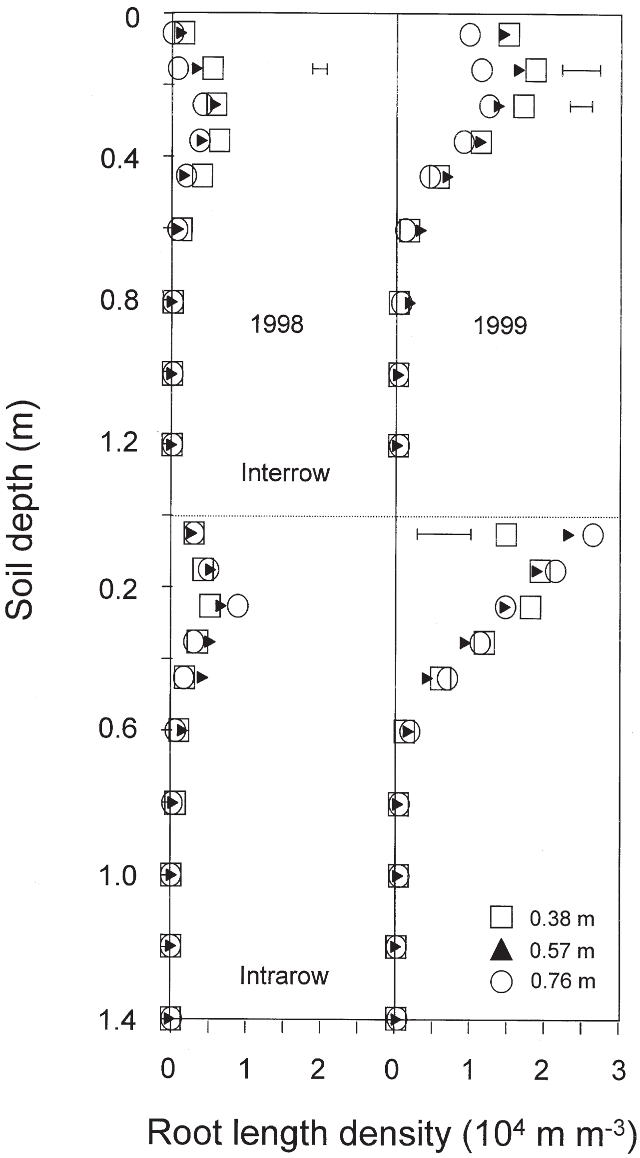

Fig. 1. Intrarow and interrow root length density as a function of soil depth for corn sown in 0.38-, 0.57-, and 0.76-m rows. Root length was determined at the time of silking on 20 July 1998 and 27 July 1999. Bars indicate LSD values.

production in 1998 and 1999 (data not shown). Residue biomass was greater for corn grown in narrow (0.38 m) rows than in conventional (0.76 m) rows. The response in residue biomass to row spacing, however, depended on corn hybrid in 1999 as demonstrated by a significant ($P = 0.05$) interaction between hybrid and row spacing. Corn row spacing did not affect harvest index in 1998 or 1999 (Table 1).

The rooting depth of corn was observed to be about 0.9 m in this study (Fig. 1) and is consistent with other observations for corn in the north-central USA (Nickel et al., 1995), southeastern USA (Vepraskas et al., 1995), and Canada (Dwyer et al., 1988). Although not evident in Fig. 1, roots (root length density $< 0.05 \times 10^4$ m m^{-3}) were detected below 0.9 m in 50% of the plots and below 1.1 m in 25% of the plots both years. Also apparent from Fig. 1 is that root length density was smaller in 1998 than in 1999. Averaged across treatments, root length density in the upper 0.5 m of the soil profile equaled 0.38×10^4 and 1.34×10^4 m m^{-3} in 1998 and 1999, respectively. The greater root length density in 1999 may be attributed to greater seasonal precipitation. Wetter soils, however, could not account for the higher root length densities. In fact, at the time soil core samples were extracted from plots, water content in the upper 0.6 m of the soil profile averaged 0.37 and 0.29 m^3 m^{-3} across treatments in subsequent years. The soil was likely drier in 1999 as a result of less precipitation received before extracting samples in 1999 than in 1998. For example, 53 mm less precipitation was received within 7 d or 60 mm less precipitation was received within 14 d of sampling in 1999 than in 1998. Our finding of more prolific rooting in drier soil is consistent with recent observations by Merrill et al. (2002).

Root length density was typically greater in the intrarow than interrow position of corn rows (Fig. 1). In fact, the maximum root length density (2.8×10^4 m m^{-3}) in this study was observed in the upper 0.1 m of the soil profile in the intrarow of 0.76-m rows. This maximum root density is equal to that found in the intrarow of corn previously grown in 0.76-m rows in Minnesota (Bauder et al., 1985). Averaged across years, root length density at a depth of 0 to 0.5 m in the intrarow and interrow was 0.88×10^4 and 0.91×10^4 m m^{-3} for corn grown in 0.38-m rows, 0.96×10^4 and 0.80×10^4 m m^{-3} for corn grown in 0.57-m rows, and 1.04×10^4 and 0.59×10^4 m m^{-3} for corn grown in 0.76-m rows, respectively. Bauder et al. (1985) also observed that root length density of corn grown in 0.76-m rows was greater in the intrarow. Their observations of corn grown under conventional autumn tillage indicated that root length density in the upper 0.3 m of the soil profile was about 0.8×10^4 m m^{-3} in the intrarow and 0.2×10^4 m m^{-3} in the interrow.

The influence of corn row spacing on root length density was not consistent across years. Root length density differed among row-spacing treatments at some depth in both the interrow and intrarow positions in 1999 but only differed among treatments in the interrow position in 1998 (Fig. 1). Root length density in the interrow tended to be greater for corn grown in 0.38-m rows than in 0.76-m rows. Differences in root density in the interrow across years were found over a depth interval of 0.1 to 0.3 m in the soil profile. In contrast, root length density in the intrarow was greater for corn grown in 0.76- or 0.57-m rows than for corn grown in 0.36-m rows (Fig. 1). Differences in root density in the intrarow were found near the soil surface. The higher root density in the intrarow of 0.76-m rows is consistent with the closer spacing of plants within the 0.76-m rows than 0.36-m rows.

Microclimate

Differences in light interception among row-spacing treatments were observed during the 1998 and 1999 growing seasons (Fig. 2). Light interception was typically greater for corn grown in 0.38-m rows than in 0.76-m rows with differences becoming apparent in early July

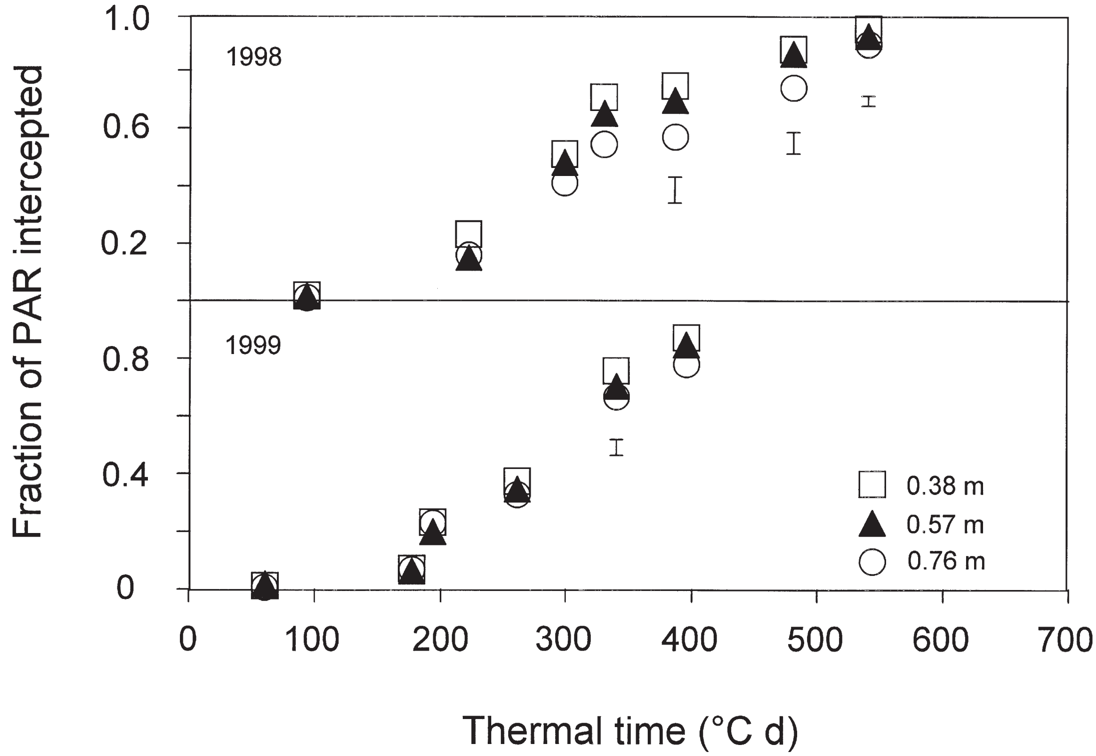

Fig. 2. Fraction of photosynthetically active radiation (PAR) intercepted by the canopy as a function of thermal time from emergence for corn sown in 0.38-, 0.57-, and 0.76-m rows during the 1998 and 1999 growing seasons near Morris, MN. Bars indicate LSD values.

when stems were rapidly elongating (V10 stage of development) and plants were more than 0.5 m in height. These differences in light interception among treatments, which persisted until tasseling in 1998, reflect those associated with leaf area or leaf architecture (i.e., distribution) within the canopy. Since leaf area or leaf distribution was not observed in this study, leaf area index (LAI) was estimated according to:

$$I_s/I_o = \exp(-\kappa \mathrm{LAI}) \quad [3]$$

where κ is the light extinction coefficient for corn and was assumed to vary with row spacing according to Flenet et al. (1996). Estimates of LAI at the time light interception was measured both growing seasons indicated no differences ($P > 0.1$) in leaf area among row-spacing treatments. Scarsbrook and Doss (1973) also found that corn row spacing influenced light interception without necessarily affecting LAI, but their results varied with plant population and hybrid. We assume that differences in light interception among row-spacing treatments were associated with differences in leaf distribution within the canopy with a more uniform distribution of leaves in the canopy of narrow-row versus conventional-row corn.

Daily soil evaporation was affected by corn row spacing, but differences among treatments were infrequently observed each year (Table 2). On days when row spacing influenced soil evaporation, evaporative loss was smaller for corn grown in narrow (0.38 m) rows rather than conventional (0.76 m) rows. Differences in daily soil evaporation between narrow-row and conventional-row corn ranged from about 0.1 to 0.5 mm. Less evaporation in narrow-row corn may be caused by greater shading of the soil surface (more radiation intercepted by the canopy) as well as reduced convection (Yao and Shaw, 1964) or advection (Hanks et al., 1971) between adjacent crop rows.

Soil temperatures during early canopy development

Table 2. Daily soil evaporation from interrows of corn grown in 0.38-, 0.57-, and 0.76-m rows near Morris, MN.

Year	Row spacing	Soil evaporation									
		mm d^{-1}									
1998		3 June	4 June	22 June	30 June	1 July	8 July	9 July	13 July		
	0.38	1.4	1.1	1.3	0.9	0.8	0.8	1.0	0.9		
	0.57	1.3	0.9	1.3	0.9	0.8	0.7	0.9	1.0		
	0.76	1.4	0.9	1.4	1.1	0.9	1.1	1.2	1.2		
	LSD†	ns	ns	ns	ns	0.1	ns	ns	ns		
1999		26 May	14 June	15 June	16 June	21 June	1 July	6 July	12 July	13 July	14 July
	0.38	1.1	1.4	1.1	0.8	1.3	1.2	1.2	0.6	0.4	0.3
	0.57	1.1	1.3	1.0	0.7	1.3	1.7	1.5	0.6	0.4	0.3
	0.76	1.2	1.4	1.0	0.7	1.4	1.7	1.5	0.8	0.5	0.4
	LSD	ns	ns	ns	ns	ns	0.4	ns	0.1	0.1	ns

† LSD is least significant difference at $P \leq 0.1$.

Table 3. Average daily soil temperature, from shortly after emergence to about the V10 stage of development, at a depth of 0.01, 0.05, and 0.10 m within and between corn rows spaced 0.38, 0.57, and 0.76 m apart near Morris, MN.

		Between rows			Within rows		
Year†	Row spacing	0.01 m	0.05 m	0.10 m	0.01 m	0.05 m	0.10 m
		°C					
1998	0.38	20.0	19.4	19.0	19.7	19.3	18.9
	0.57	20.6	19.4	19.0	19.5	19.5	19.0
	0.76	20.7	19.7	19.3	19.6	19.2	19.1
	LSD‡	0.2	ns	ns	ns	ns	ns
1999	0.38	22.7	21.1	20.5	22.8	21.3	20.5
	0.57	23.3	21.1	20.9	22.7	21.0	20.7
	0.76	23.4	21.4	20.7	22.5	20.9	21.0
	LSD	0.5	ns	ns	ns	ns	0.2

† Soil temperatures averaged from 21 May to 24 June 1998 and from 27 May to 24 June 1999.
‡ LSD is least significant difference at $P \leq 0.1$.

varied among the row-spacing treatments (Table 3). This is exemplified by differences among treatments that were observed in the interrow near the soil surface. Soil temperature at a depth of 0.01 m was about 0.5°C cooler in the interrow of corn grown in 0.38-m rows than that grown in 0.57- and 0.76-m rows. These differences in daily temperatures are largely due to daytime heating rather than nighttime cooling as portrayed in Fig. 3. Indeed, on this clear day in June 1999 when plants were about 0.5 m tall and near the V10 stage of development, nighttime soil temperatures in the upper 0.01 m of the soil profile were nearly the same in the interrow and intrarow for the row-spacing treatments. Soil temperatures during the daytime, however, differed among treatments. Maximum soil temperatures reached 55, 47, and 42°C in the interrow of corn grown in 0.76-, 0.57-, and 0.38-m rows, respectively. In contrast, maximum temperatures were 43, 40, and 42°C in the intrarow of the respective row-spacing treatments. These differences in soil temperature can affect root and shoot growth as optimum growth is achieved at soil temperatures between 25 and 35°C (Shaw, 1988). An apparent spike in near-surface soil temperatures occurred near solar noon in the interrow of corn grown in 0.57- and 0.76-m rows; this spike was not apparent in the interrow of corn grown in 0.38-m rows (Fig. 3). This spike in soil temperature is more apparent in wider rows due to the unobstructed penetration of radiation through the canopy near solar noon. On this clear day in June 1999, the daily average temperature at a depth of 0.01 m was 28.8, 26.9, and 26.1°C in the interrow (LSD = 1.8°C) and 26.8, 26.3, and 26.5°C (no significant difference) in the intrarow of corn grown in 0.76-, 0.57-, and 0.38-m rows, respectively.

Crop water use was determined from measurements of precipitation, soil water extraction, and water flow below the root zone. Drainage of water occurred from the soil profile both years. Averaged across treatments, 85 and 88 mm of water drained from the profile during the 1998 and 1999 growing season. Crop water use from the time of emergence to physiological maturity varied from 540 mm in 1998 to 475 mm in 1999 (Table 1). These values are in the range for corn grown in west-

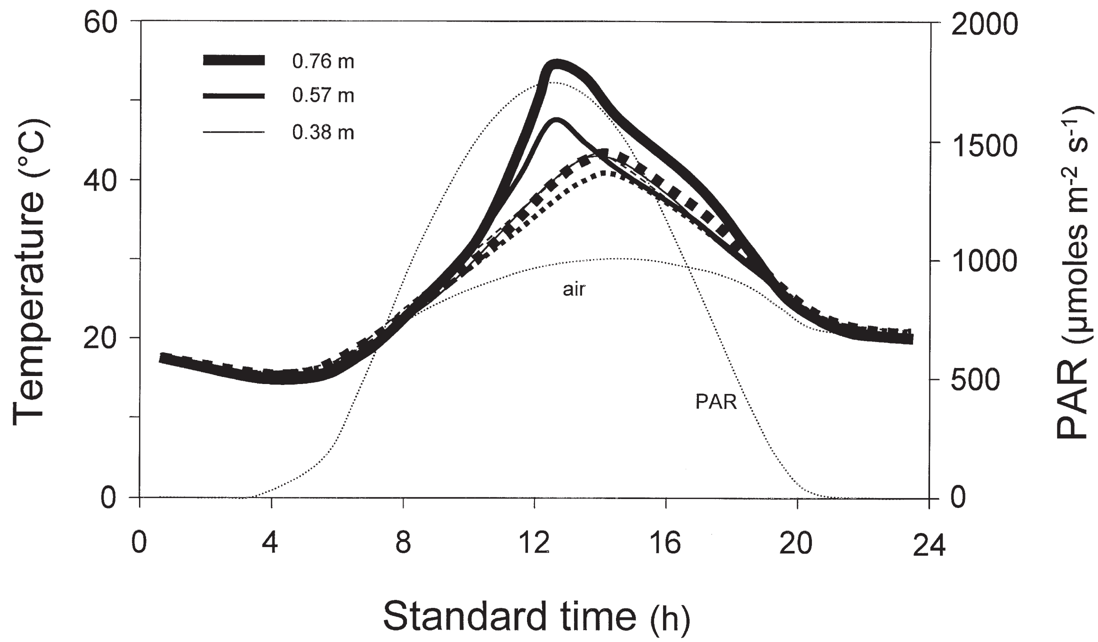

Fig. 3. Diurnal trend in soil temperature, air temperature, and photosynthetically active radiation (PAR) on 24 June 1999 near Morris, MN. Soil temperature was measured at a depth of 1 cm in the intrarow (dashed lines) and interrow (solid lines) of corn sown in 0.38-, 0.57-, and 0.76-m rows.

central Minnesota (Lindstrom et al., 1982) and in Iowa (Yao and Shaw, 1964). Corn row spacing did not affect water use in 1998 but did influence water use in 1999. Water use was greater for corn grown in narrow, 0.38-m rows than in wide, 0.57- and 0.76-m rows. Narrow-row corn consumed more water than conventional-row corn as a result of greater soil water extraction in 1999. For example, soil water extracted by corn grown in 0.38-, 0.57-, and 0.76-m rows equaled 150, 137, and 122 mm, respectively. Differences in soil water extraction may be due in part to a more uniform root distribution in narrow-row versus conventional-row corn. Water use efficiency was about 20 kg ha^{-1} mm^{-1} both years. No difference in water use efficiency was found among row-spacing treatments.

CONCLUSIONS

Narrow-row corn (row spacing less than 0.76 m) has been advocated in recent years as a method to bolster production in the northern U.S. Corn Belt. Although previous studies do not universally agree on the benefits (e.g., higher grain production) of sowing corn in narrow rows, speculation abound concerning the cause of these higher yields for corn grown in narrow rows versus wide conventional rows. Findings from this study suggest that grain production of narrow-row corn equals, or may even exceed, that of conventional-row corn. In the absence of weed competition, corn grown in narrow rows had higher root densities, occasionally suppressed soil evaporation, and abated daytime soil temperatures. Narrow-row corn also intercepted more PAR but used an equivalent amount or even more water than conventional-row corn. The results of this study suggest that corn grown in narrow rows will establish a more uniform root and leaf distribution that may promote more effective utilization of light and water resources.

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